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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

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ABSTRACT

DOE has established a number of broad programs aimed at reducing fuel consumption. Several programs address the R&D of ground transportation propulsion alternatives to the conventional spark-ignition engine. NASA Lewis is responsible for managing the effort between the Government and industry teams involving American and foreign companies. Thus, existing NASA SR&QA procedures were modified/adapted to these R&D programs and implemented to assure that the test hardware design intent was met, the hardware was not hazardous to personnel, it would demonstrate reliable operation, and it would help establish the future R&D quality assurance and maintainability requirements. This successful low-cost approach might be applicable to other similar projects.

INTRODUCTION

The Department of Energy (DOE) Office of Vehicle and Engine Research and Development has established a number of broad programs aimed at reducing highway fuel consumption. The Heat Engine Highway Vehicle Systems Program is one such program. It is directed toward the development of possible alternatives to the conventional spark-ignition engine. Implementation of the program is through a joint effort between the U.S. Government and U.S. and foreign industry in development activities designed to permit the U.S. automotive industry the option to enter into preproduction engineering of these alternative engine systems.

Within the broad scope of this technology development program two alternatives are being investigated: one is developing the technology for our automotive Stirling engine, and the other is developing the technology for an automotive gas turbine engine. Each of these involves unique analytical as well as technological approaches and associated development needs. Success in developing these alternatives depends on finding proper solutions to the challenges presented by the selected alternatives. The magnitude of these programs, the extensive publicity of their existence, and the objective they are to achieve resulted in an unusually high program visibility as well as almost an expectation or demand of technological success.

To meet this challenge and to assure meeting the intent of the corresponding designs, senior management at NASA Lewis issued a directive to implement the product quality assurance methodology so successfully implemented in previous programs. These programs, however, dealt with aerospace technology. Thus, in meeting the directive, the usual aerospace approach to quality assurance was overbearing and had to be modified to be as compatible as possible with the quality assurance methodology already in place within the U.S. industry being funded to carry out these research and development programs. Yet these quality assurance procedures must be compatible with

the special needs and constraints of the complex nature of the R&D programs. The process of evolving and implementing quality assurance procedures in R&D programs using Stirling and gas turbine engine development as illustrative examples is described herein. Gas turbine engine technology development involved efforts by contractor teams - namely, Garrett/Ford and Detroit Diesel Allison (DDA). The latter is used as an illustrative example of gas turbine engine technology development because of the author's familiarity with the DDA efforts.

SYSTEM DESCRIPTION

In discussing the process of evolving and implementing quality assurance in R&D programs it is necessary to describe each alternative system.

One of the selected alternatives is the development of the automotive Stirling engine (ASE) illustrated in figure 1. The most pronounced characteristic of the ASE is its external combustion and closed-loop working gas arrangement to convert heat into work energy. The cycle is illustrated in figure 2. The expansion and contraction of the working gas, as it moves back and forth between the hot and cold spaces within the engine, causes the pistons to reciprocate and thus rotate the drive shaft. Although almost any type of gas may be used as a working fluid in the Stirling cycle, gaseous hydrogen, because of its heat-transfer characteristics and the resulting high power output, has been selected. The combination of high-temperature environment present in the combustor with the gaseous hydrogen working fluid results in very demanding conditions in which structural materials must survive.

The other selected alternative is the automotive gas turbine propulsion system. Figure 3 shows a two-shaft regenerative gas turbine engine. It operates by continuously combusting a fuel and high-pressure air mixture. The resulting hot expanding gases are then directed through the turbines where the energy from their high pressure and temperature is converted to rotational energy to drive the compressor and provide power to the output shaft.

The gas path facilitating this function is illustrated in figure 4. The key to successfully developing this alternative is the introduction of ceramic materials in selected components (fig. 5). These components are essential to increasing the turbine operating temperature regime and thus the efficiency. Introducing ceramic material components entails extensive development of manufacturing processes, material characterization techniques, nondestructive evaluation methods capable of consistently detecting 10- μ critical size defects, process controls, and numerous other factors.

PROGRAM MANAGEMENT STRUCTURE

The Department of Energy (DOE) was designated by Congress (Public Law 95-238, Heat Engine Bill) as the Government agency responsible for initiating programs to develop unique automotive and fuel technology. Under an inter-agency agreement with DOE, the National Aeronautics and Space Administration's Lewis Research Center was given the project management responsibility for these alternative automotive propulsion system projects. Within Lewis, the Energy Directorate was established to develop, conduct, and direct these

projects. The Director of Lewis has instructed the Chief of the Reliability and Quality Assurance Office in conjunction with the Director of Energy Programs to develop and implement reliability, quality assurance, and project safety programs within the energy projects commensurate with DOE requirements, project objectives, and overall cost effectiveness. The interrelationship among DOE, NASA, and the contractor is illustrated in figure 6.

During 1978-1979, the U.S. Government negotiated appropriate contracts with U.S. industry to carry out the R&D effort. The industry team for the ASE program is shown in figure 7. Mechanical Technology Inc. (MTI) of Latham, New York, is the prime contractor responsible for coordinating engine and component development as well as transferring Stirling cycle engine technology to the United States. United Stirling (Sweden) AB and Co. (USAB) is the major subcontractor for engine design, development, testing, and manufacture. USAB has successfully developed the analytical capability characterizing the Stirling cycle and has reduced that capability to practice by building a 40-kW test engine. The engine (designated P-40) demonstrated that this type of engine could be developed into an automotive power train system for passenger vehicles and that it could produce favorable results. AM General Corporation of Detroit, Michigan, is the major subcontractor responsible for engine-vehicle integration. This aspect was successfully demonstrated by installing P-40 engines in a 1977 Opel, a 1979 AMC Spirit, and a 1980 AMC Concord. As a result of these successful demonstrations, this industrial team has now completed the design and manufacture of four automotive Stirling engines designated MOD-I (fig. 1). One of the engines has been installed in an AMC Lerna passenger vehicle for transient testing. The other three are being tested in engine test stands at MTI in Latham, New York, and Malmö, Sweden, to obtain performance data, verify design, and establish component development technology.

Figure 8 illustrates the U.S. industry team responsible for developing the AGT 100 engine system. Detroit Diesel Allison (DDA), a Division of General Motors in Indianapolis, Indiana, is the prime contractor responsible for developing the engine power train and accomplishing the overall program. Success of this program hinges on the team of major subcontractors responsible for developing the ceramic components: Carborundum, silicon carbide components; Corning Glass, aluminum silicate regenerators; GTE, silicon nitride rotors. Other divisions of GM form the remainder of the major participants responsible for engine-vehicle integration, testing, component assemblies, electronic controls, marketing studies, and other functions listed in figure 8.

RELIABILITY AND QUALITY ASSURANCE REQUIREMENTS AND IMPLEMENTATION

A consistent set of R&QA requirements was established for automotive propulsion R&D programs. It requires the contractor to plan, maintain, and implement a product assurance program. This also entails system safety and reliability functions. The product assurance requirements, however, apply to all critical hardware. The critical hardware is identified by the contractor and approved by NASA project management. In using this approach, both the contractor and Government project office are spared the excessive trivial problem of tracking noncritical hardware and the documentation such tracking can entail. The list of critical parts is periodically reviewed and adjusted to resolve arising problems.

These product assurance requirements are not intended to impose a separate or unique system on the contractor. The contractor's existing product assurance system is considered adequate upon satisfactory demonstration to NASA Lewis that it fully meets the product assurance requirements envisioned for these programs. Unfortunately, in the case of USAB, these requirements did impose a unique system because the company did not have an acceptable quality assurance system in place.

It is the contractor's responsibility to prepare, implement, and maintain a detailed product assurance plan. In this plan the contractor describes how compliance with requirements is ensured and identifies an individual as a cognizant contact. The plan is submitted to NASA Lewis for review and approval 30 days after contract initiation. It is very important to understand that although the R&QA requirements are the same for each contractor the method of implementation is adjusted to the individual contractor's system; hence, the quality assurance plans are not expected, nor are they required, to be identical in format or methodology.

The requirements consist of two basic elements: reliability and quality assurance. The reliability element entails design reviews and system safety analyses. Design reviews require the contractor to establish and conduct a program of planned, scheduled, and documented reviews of the system, subsystem, and component level. Participation is required by cognizant personnel from design, fabrication, test, reliability, safety, and other appropriate elements of the contractor's organization. However, since some of the elements just identified may not exist as such at a given contractor's organization, he identifies his design review process in the quality assurance plan. Once the plan is approved by NASA, the contractor must live up to the responsibilities and mode of operation he has structured. In connection with these reviews, the contractor is required to submit to NASA the following:

1. Notification is necessary 10 working days before each review of the firm date, time, location, and material information to be reviewed.
2. Design Review Reports are required within 10 days. These reports contain the information presented at the review, the actions to be taken, the organizational elements or individuals responsible for carrying out the action items, and the attendees present at the review.

A system safety analysis requires the contractor to employ existing rigorous analysis techniques to ferret out design weaknesses and determine possible modes of failure. The primary objective of these analyses is to identify critical failure areas, affect removal of susceptibility to such failures or their effects from the system, and to minimize the risk. The system safety analyses are to be a major factor in design and management reviews. They are to provide criteria useful for

1. Determining need for fail-safe design features
2. Determining need to select more reliable materials, parts, devices, or components
3. Identifying single failure points
4. Supporting hazard analysis tasks
5. Assuring that future test planning is responsive to known or suspected potential failure modes
6. Establishing future mandatory quality inspection points

The quality assurance element entails maintenance by the contractor of an effective and timely quality system to discover and correct at the earliest practical point defects or other unsatisfactory conditions. This is intended to determine material and product quality from the time raw materials are purchased until completion of the article, whether the article is to be delivered to the Government or used in the program. The basic objective is to provide recorded evidence of the extent of meeting the design intent. This is accomplished in the form of a series of actions as follows:

1. Drawing and Change Control - to assure that articles are purchased, fabricated, inspected, and tested to the latest applicable drawing or specification.

2. Procurement Source Control - exercise effective control over procurement sources to ensure that materials, supplies, components, and services meet the quality as well as design requirements. Thus, an effective purchase order control and an assurance of conformance with requirements of the purchase order are essential.

3. Material Identification, Handling, Storage - to control the raw and fabricated materials and to determine their conformance to applicable specifications and drawings. In so doing, the contractor separates and prevents the use of materials which do not conform to the requirements or are awaiting the completion of test results and Material Review Board actions. These controls are maintained from the time the material is received until its use in the program is completed.

4. Identification Control Procedure - assignment of appropriate part number, change letter, and serial numbering system for all major parts and subassemblies.

5. Inspections, Tests, and Process Controls - inspections and tests of critical parts, components, and assemblies to ensure conformance to applicable drawings and specifications. In addition, inspections and controls are established over processes to ensure compliance with quality requirements which are not readily detectable or measurable by inspection and test of the finished article. The contractor is responsible for maintaining a suitable inspection of his tools and gages, and for assuring their proper calibration. Appropriate inspection status indications are maintained by the contractor.

6. Nonconforming Articles - identify and separate such articles from normal work operations. When the contractor wishes to use a nonconforming article in the program operations, he prepares a suitable quality assurance report (QAR), an example of which is shown in figure 9. The QAR is submitted to the contractor's Material Review Board (MRB) for disposition. The MRB consists of a cognizant engineer and a cognizant quality assurance representative. Decisions to accept nonconforming articles by the MRB are documented using the QAR. It shows the details of nonconformity and the appropriate disposition actions such as repair, use as is, or scrap. Concurrence with the disposition actions by the contractor and NASA project managers is required.

7. Corrective Action - to correct conditions which have resulted or might result in substandard or defective materials, parts, components, or services. These actions are documented using the QAR or any other suitable means to correct existing deficiencies and to minimize their occurrence in the future.

8. Equipment Log for Engine Systems - to document the continuous history of the item. This documentation is maintained throughout the inspection, assembly, and test of engine systems. The log is maintained in chronological order and accounts for all time periods including idle periods. Log entries are self-explanatory and may include the following: date of assembly and

disassembly, identity of test or inspection, environmental conditions, characteristics being investigated, performance parameter measurements, complete identification of instrumentation, failure observations, applicable failure report references, accumulated operating time on critical items, configuration identification of critical parts in the system (by serial numbers), nonconforming article identification, documentation reference, repair and maintenance records, record of pertinent, unusual, or questionable occurrences, and identity of the individual operating the equipment and making entries.

9. Operating Time Records - a consolidated record of operating times for each critical engine component used in the test program. The engine components are identified by part and serial number. These records are to be included in the final test report.

10. Failure Reporting - functional failure occurring in the test program. A failure notice is written immediately when a failure occurs, and this report is sent within 24 hours by the originating function to the NASA project manager or his representative. In case of the ASE program, the QAR (fig. 9) is used very effectively for this purpose. The failure notice, which is filled out as completely as possible at the time of the failure, is written in clear, concise language. If appropriate, a followup failure analysis is submitted to the NASA project manager or his representative no later than 30 days after a failure. Such reports usually contain a complete description of the failure, an analysis of the causes, recommendations for corrective action, and the corrective actions taken. The NASA project manager or his representative is required to approve the failure analysis and the corrective action taken.

These general requirements are implemented by the various contractors using the quality assurance methodology already in place at their respective facilities. By using his own specific quality assurance plan the contractor makes a purposeful commitment of the available quality assurance methodology, personnel, and resources to attain the intent of the design. This commitment results in an active program which also provides thorough documentation of various factors affecting hardware quality and compliance to or deviation from requirements and their effects on the intent of the design. In R&D programs where interactions between unknowns or variables are not easily predictable, such documentation provides consistency of information as well as a more orderly resolution of problems. For example, in the early stages of the ASE program, using QAR's to report failures highlighted a problem which was successfully resolved by a minor design change. At the time, the problem was being identified as check valve failure. The identification was not quite proper, because the check valve failure was actually a failure of an O-ring in the check valve assembly. As illustrated in figure 10, check valve failures were unacceptably frequent. A design change to more properly accommodate the troublesome O-ring arrangement resulted in a favorable outcome. Although this failure mode still occurs, it is less frequent and more easily controlled by procedures.

Both MTI and DDA successfully implemented the R&QA requirements in their R&D programs. Each contractor faced a unique set of problems and had to resolve them in his own way. There is no intent to compare one against the other or to determine that one approach was better than another. It seems appropriate to highlight the unique problems each prime contractor faced.

In the case of Automotive Stirling Engine Program, the most difficult problem was implementing the quality assurance program at the major subcontractor USAB. USAB was the source of the knowledge technology to be transferred to United States and was responsible for designing and manufacturing the engines. The company was basically a research-oriented organization with limited personnel resources. Influx of numerous parts, test operations, and all other activities associated with the program overwhelmed their capabilities. The quality assurance program was not consistent to the level required of the prime contractor. The situation at MTI was not much different. There was no choice but to establish a product quality assurance program capable of serving the program needs. MTI's program management earnestly supported such action with very successful results. One of the examples is the use of the QAR system (fig. 11) among the various participants. The originating participant submits the QAR to MTI who redistributes it to all participants. When the issue is resolved, completed QAR's are distributed to the participants clearly stating the resolution. This system was very useful in exchanging experiences between test operations personnel and in finding solutions to nagging detailed problems without tying up the designer's time.

The language, use of standard Swedish tolerance tables, geographic distances, and time zone differences presented additional complications. These complications were not insurmountable, but additional time was required to fully implement quality assurance plans. Since all parties involved diligently applied their best judgments, a successful implementation of R&QA practices in an R&D program resulted.

The only shortcoming is that system safety analysis techniques were not more extensively employed when evaluating the designs and operations.

The challenge faced by DDA was due to the extremely fast advancement of ceramic technology which appeared to be at hand, but not fully so. The designers were faced with material properties information that was not completely defined. An additional factor was, and still is, the highly proprietary nature of ceramic technology development. DDA has an elaborate and very effective quality assurance program in place, but proprietary restrictions adhered to by the ceramic parts suppliers precluded effective extension of DDA's quality assurance program to the vendors. This resulted in approaches by DDA to obtain the necessary material properties information. Eventually these approaches resulted in the suppliers defining their process controls more precisely. In order to better understand behavior of ceramic components and assure their acceptability for engine builds, DDA employed evaluation rigs and tests in which ceramic parts were exercised in stress environments at, or exceeding, the levels expected in engine operation. Since a system of codes designating process variants known only to the supplier was devised, the prime contractor can relate rig data with process code. Part failures in rig tests are investigated by DDA's materials experts and causes are identified. Such data obtained by the prime contractor are transmitted readily to the supplier, thus influencing his process control. In turn, the supplier is obligated to keep the prime contractor informed of process changes by adjusting the code.

Use of evaluation rigs also circumvents, albeit temporarily, the immediate need of extremely powerful nondestructive test methodology to detect

the aforementioned 10- μ critical size defect. Indications are that more effective and extensive manufacturing process controls may partially alleviate this problem, but much work remains to be done.

This program employs a delegation of quality assurance activities from NASA Lewis to Defense Contract Administration Services (DCASPRO). The use of these services is unusual in an R&D program, and it may be the first time it has been done. The delegation allows NASA to have an inspector at all the critical activities of this program. The inspector is to observe, report, and ensure that corrective action as concurred by NASA is carried out. The definition of delegation and personnel assigned to carry out the task resulted in a most rewarding experience. The inspector is very effective, and he has established a very respectable rapport with his counterparts at DDA. As a result, he is aware of all the major and most of the minor problems of this program, and his advice is readily sought and, if applicable, heeded. NASA Lewis has retained the full authority under the delegation.

To facilitate the assembly of the AGT 100 engine, DDA's management imposed on itself an accelerated build program. The objective of the program was to have all 392 parts in finished stores before assembling the initial engine. That meant that all the standard inspection and quality assurance activities normally carried out by DDA also had to be accomplished for the 392 parts. To achieve this and provide proper priority for all the necessary activities, DDA established a task force in which engineering, design, manufacturing, and quality assurance functions were represented. Quality assurance functions were represented by a senior quality assurance engineer from experimental inspection. Our inspector was invited to attend DDA's executive reviews as well as task force meetings. This cooperative effort with DDA's senior quality assurance engineer provided rapid and, from a quality assurance point of view, orderly and proper progression of the program. For the first build, all parts were inspected completely (100 percent) if their quality, materials compatibility, and compliance with the drawing requirements could not be properly verified by previous inspection records, certifications, etc. The system is a very orderly, common sense one which is flexible to suit the needs of the program without compromising quality.

This approach with DDA management's unequivocal backing resulted in completing a difficult job in a rapid, thorough, and exemplary manner. DDA's management recognized the contribution these team members have made to the program's success by accomplishing the assigned task with skill and with interest in meeting cost targets while obtaining quality parts.

CONCLUDING REMARKS

Management's commitment to implementing quality assurance in R&D programs provided the needed visibility to quality assurance activities. It also facilitated effective use of failure reporting as a way of highlighting re-occurring problems. Management's actions on the recommendations for corrective actions provided stronger impetus in affecting these corrective actions.

The overall product quality assurance program has been successfully implemented in R&D projects and has contributed to their successful progress. However, some facets of the product quality assurance program have been partially implemented. One of these is a more effective use of system safety

analysis techniques such as fault tree analysis (FTA), failure modes and effects analysis (FMEA), and other available techniques in the design phase of the efforts. There also seems to be a tendency not to include quality assurance functions in the design phase of the effort until final design approval has been obtained. It is recognized that there is a broad spectrum of these activities required, ranging from very minimal in a basic research program to very substantial in the manufacture of a piece of hardware to do a specific job. In these situations it becomes a matter of judgment in determining the pertinence and proper degree of implementation of the quality assurance techniques.

It is recommended that management not view product quality assurance as a quality control only. Early involvement of the quality assurance engineering function in conceptual or preliminary design phases results in a better design, more properly inspectable hardware, more reasonable requirements, more proper use of resources, less cost, etc. A more intensive and timely use of system safety analysis techniques as a design evaluation tool or method is most strongly recommended. These techniques if properly exercised can uncover undesirable weaknesses in the design before building the hardware, provide tradeoff studies leading to the most suitable approach, and help find a better approach to quality assurance planning, critical inspection points, process control requirements, etc.

These are the early, if not the first, steps in extending quality assurance functions to the origins of R&D undertakings. Adjustments of the available methodology will have to be made to comply with the unique needs of individual programs. A strong commitment by management, combined with prudent tailoring of quality assurance methods to the program needs, cannot be anything else but cost effective and successful.

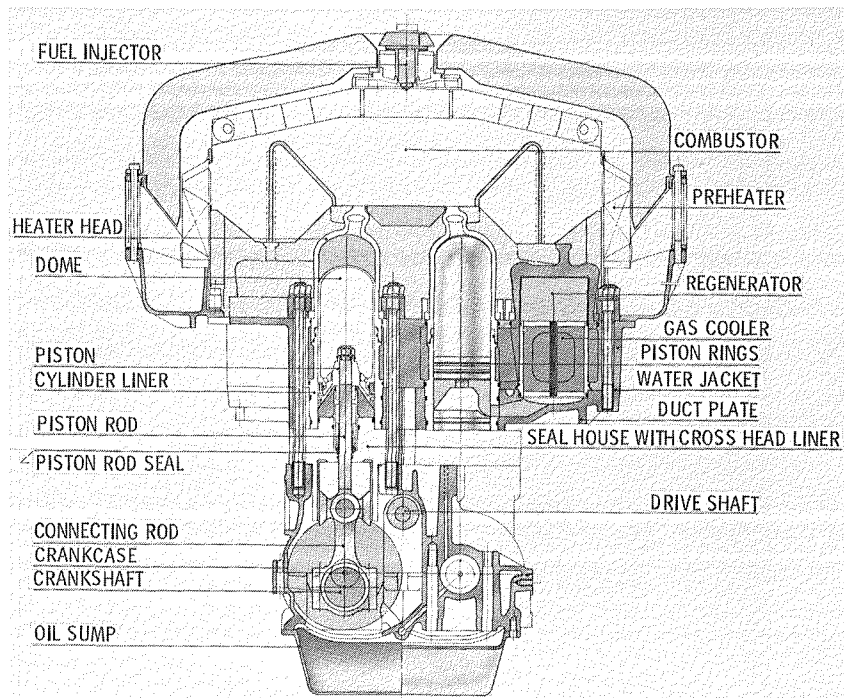


Figure 1. - Automotive Stirling engine.

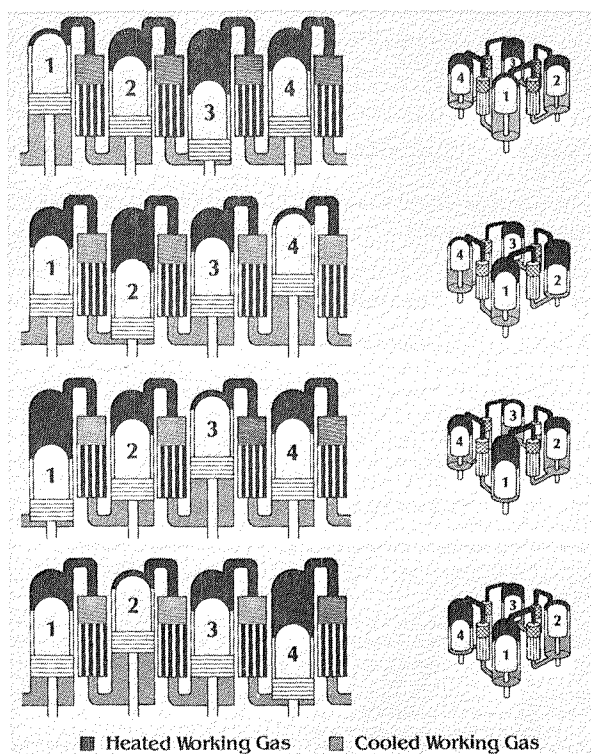


Figure 2. - Stirling engine cycle.

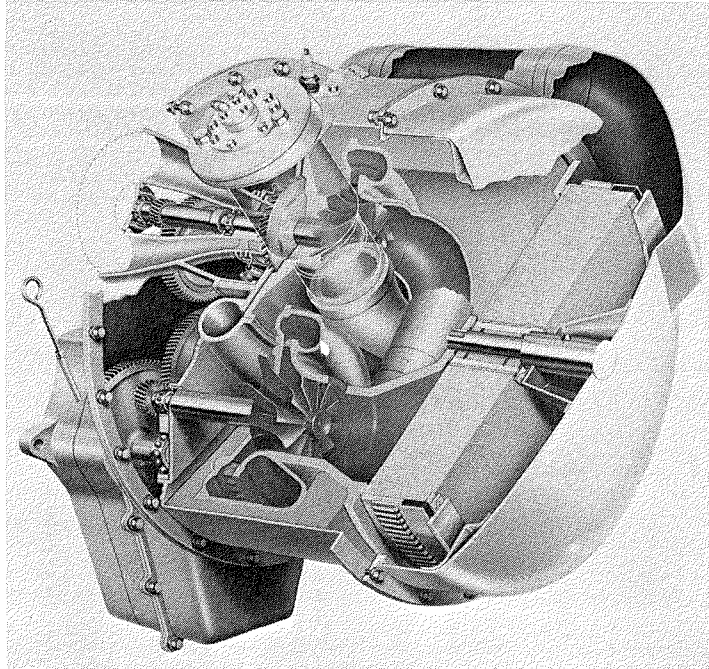


Figure 3, - AGT 100 two-shaft regenerative turbine.

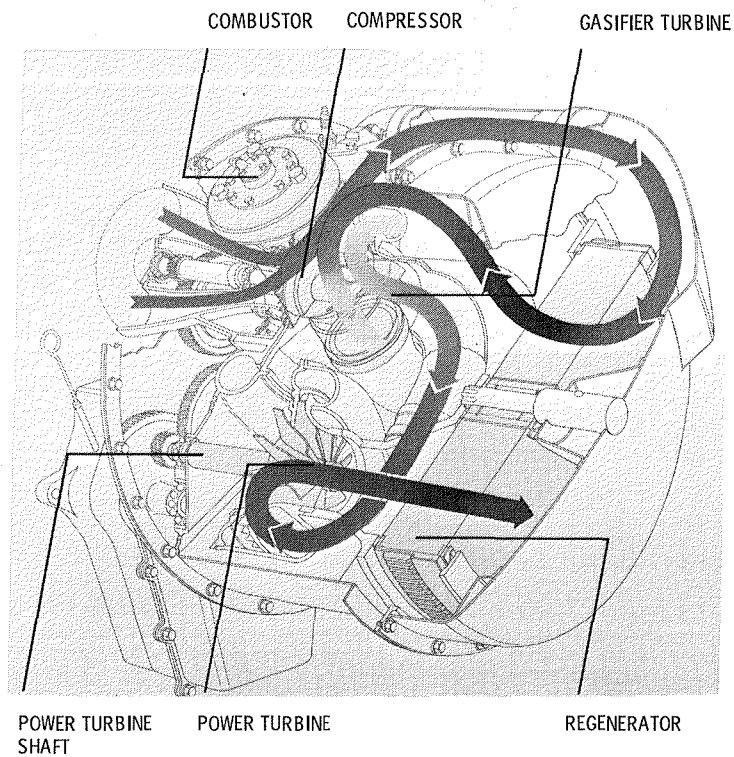


Figure 4, - AGT 100 gas path.

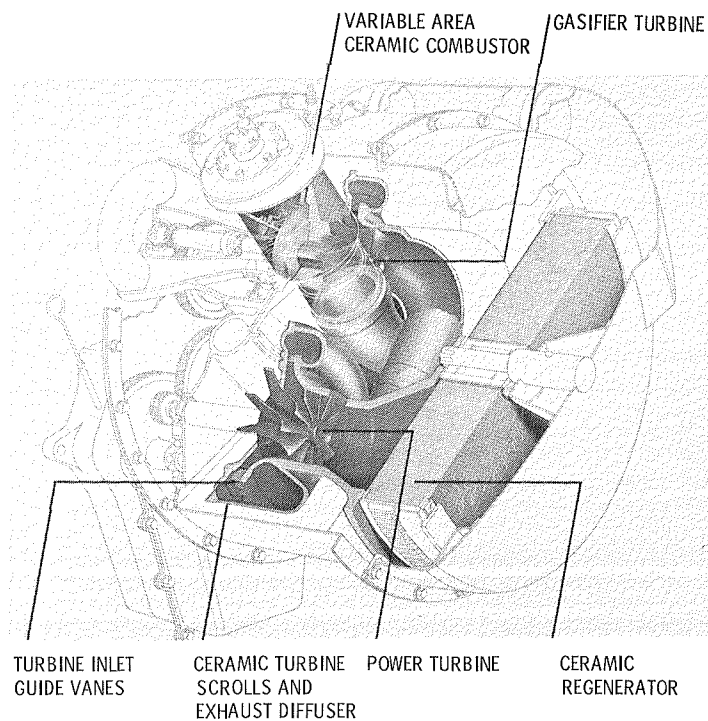


Figure 5. - AFT 100 ceramic components.

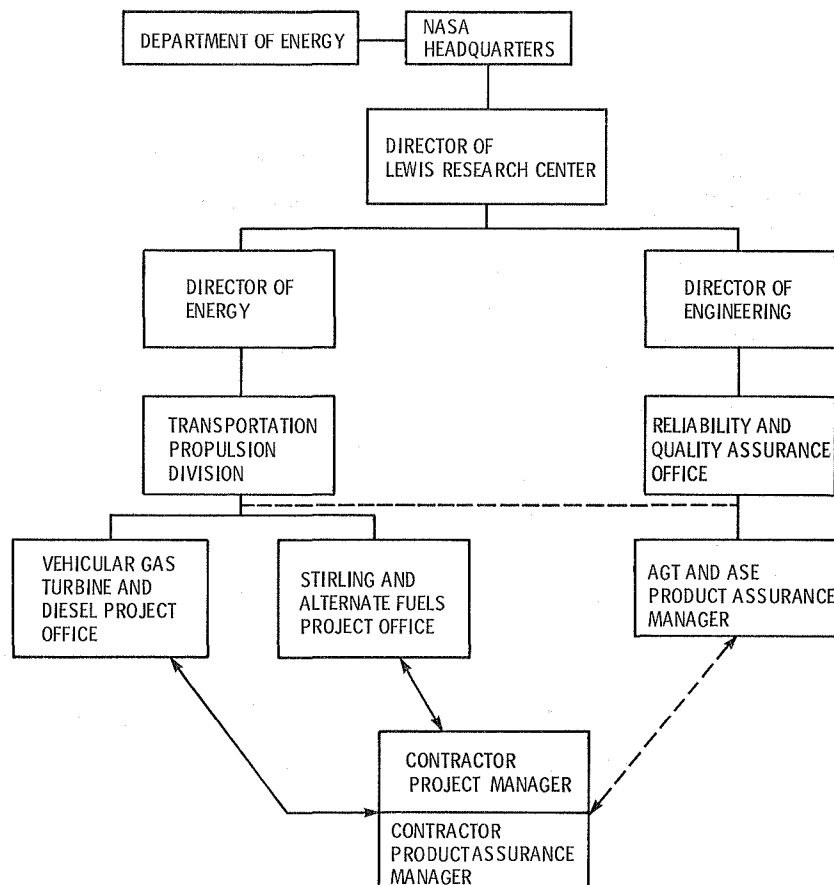


Figure 6. - Organizational relationship.

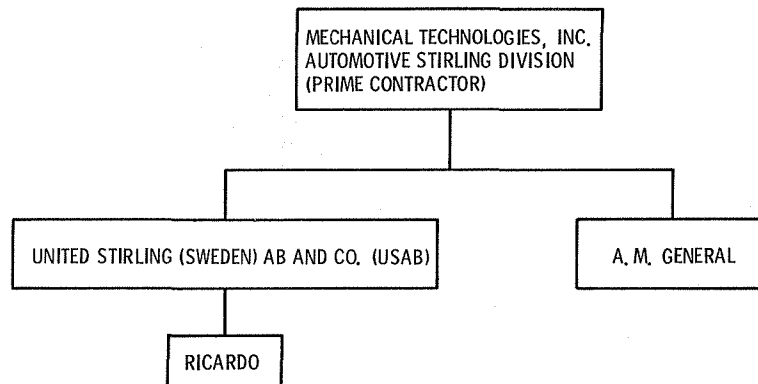


Figure 7. - Automotive Stirling engine industry team.

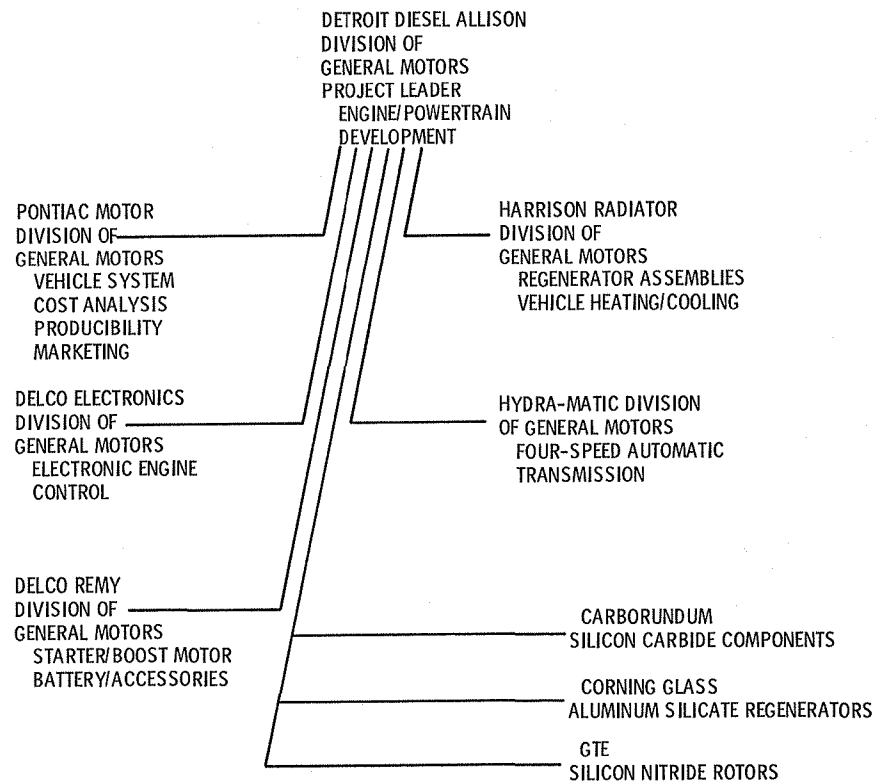


Figure 8. - Advanced gas turbine industry team.

Automotive Stirling Engine Program Quality Assurance Report				
Name of Part or Assembly				Report No.
Part No.	Serial No.	Vendor or Manufacturer		Engine Type
Prior Report No.	Test or Procedure No.	Operating Time to Failure Eng. Hours Hours on Part or Assembly		Engine No.
Description of Observation/Failure				
Effect on Engine/System Performance				
				Date
				Signature of Reporting Individual
Analysis/Disposition				
Approval Signature and Date				
Test/Development Eng.	Design Eng.	Product Assurance		Customer Concurrence Engineering
				Product Assurance

Figure 9. - Assurance report form.

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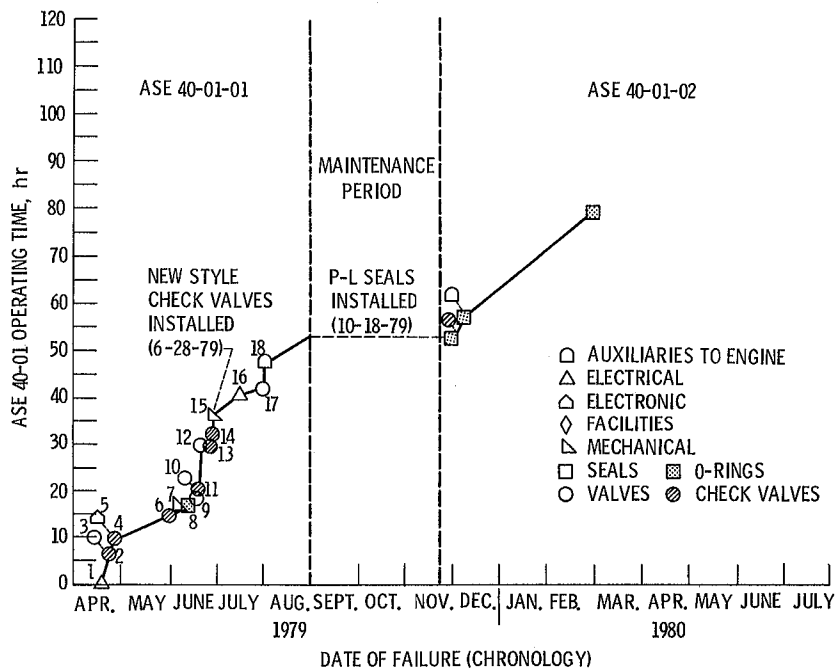


Figure 10. - Automotive Stirling engine operating time as function of failure date.

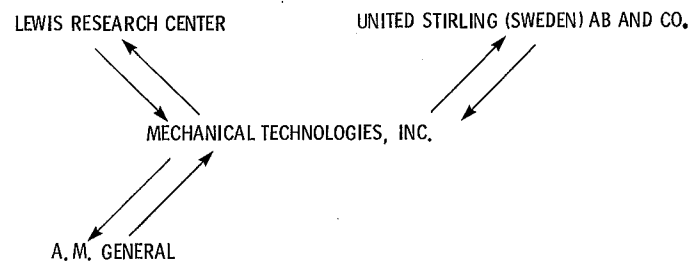


Figure 11. - Automotive Stirling engine quality assurance reporting system.

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